METHOD AND APPARATUS FOR SEPARATING AIR

5   The present invention relates to an energy
efficient gas separation system that can separate
atmospheric air into a highly enriched nitrogen fraction
and slightly enriched oxygen fraction. The nitrogen
rich air from the gas separation system contains enough
10   nitrogen to enable the air to be used as an inert
atmosphere inside tanks or vessels containing flammable
or volatile materials, such as fuels, solvents and
chemicals, to reduce the risk of fire and explosion.

     A composite hollow fibre membrane is used as the
15   gas separation medium. The membrane may consist of a
polyethersulfone fibre tube coated on the outside with a
very thin layer of selective polymer preferably
comprising polydimethylsiloxane, more preferably cross-
linked and non cross-linked polydimethylsiloxane.

20   A preferred feature of the hollow fibre membrane is that
the fibre tube is subjected to a special modification
technique that significantly increases the gas
permeability properties of the fibre before it is coated
with the selective outer layer.

25   The gas separation membrane is described in detail
in GB 2397303. The modification technique involves the
application of liquids to the outside wall of the fibre
tube, which changes the structure of the pores and the
polymer supports located near the outer surface of the
30   fibre tube. The modification technique increases the
number of pores in the fibre tube and also improves the
relative distribution of exposed open pores and polymer
supports in the outer surface of the fibre tube. The
modification technique involves soaking the outer
35   surface of the fibre tube with a solution of acetone,
displacing the acetone solution with distilled water and
then quickly drying the fibre tube, e.g. a drying time
of 60 seconds. The water drying quickly from the pores
of the fibre, has the effect of pulling on the polymer

substructures causing them to rupture, resulting in the
formation of new pores and new substructures.
Relatively rapid drying of the tube is achieved by
applying a vacuum or pressure differential to the fibre
5   tube. Repeated cycles of soaking and drying results in
a fibre tube with preferably up to twice as many pores
in its structure as unmodified fibre.

The modification process also changes the surface
characteristics of the fibre tube so that the outer
10   surface of the fibre tube is able to support a very thin
(e.g. 0.1 to 1.0 micron thick), uniform, defect free
layer of the selective polydimethylsiloxane polymer.
This combination of a very porous fibre tube and a very
thin selective coating results in a composite hollow
15   fibre membrane that has relatively high gas permeability
and a reasonable degree of gas selectivity. The
modified composite hollow fibre membrane may also be
plasma treated to further improve the gas selectivity
properties of the membrane.

20   Other polymers are also used to produce hollow
fibre tubes that are capable of supporting a coating of
polydimethylsiloxane polymer, including, for example,
polyamideimide and cellulose acetate materials. It may
well be that the fibre modification technique, or an
25   adaptation of the technique, could be applied to fibre
tubes manufactured from these alternative polymer
materials before the tubes are eventually coated with
polydimethylsiloxane.

Because the modified hollow fibre membrane has high
30   permeability properties, the membrane is able to
separate normal atmospheric air into nitrogen and oxygen
rich fractions by the application of a relatively low
differential pressure between the outside of the
membrane and the hollow core of the membrane. For
35   example, a light vacuum of about 0.5 bar applied to the

hollow core of the membrane is sufficient to draw
atmospheric air through the wall of the membrane and
allow the membrane to selectively enrich the air with
oxygen. The permeate oxygen rich air accumulates in the
5   hollow core of the membrane, whilst the retentate
nitrogen rich air remains on the outside of the
membrane.

Because the gas separation system operates under
low pressure, the separation process is energy efficient
10   and the gas separation module that contains the hollow
fibre membrane can also be of a lightweight
construction.

Incorporating a blanket of inert nitrogen rich air
above a volatile or flammable liquid stored in a tank is
15   an effective method of reducing the risk of flammable
vapour in the headspace of the tank being accidentally
ignited. To inhibit ignition and combustion, the inert
atmosphere above the flammable liquid needs to contain
less than 13% oxygen, and preferably the inert
20   atmosphere should contain between 10% and 12% oxygen,
i.e. an air composition of between 10% oxygen, 90%
nitrogen and 12% oxygen, 88% nitrogen. If the nitrogen
rich air contains less than 10% oxygen it would provide
an extremely inert atmosphere.

25   A cost effective nitrogen inerting system could
have various end use applications, including the
inerting of fuel tanks on board aircraft, fuel tanks on
board marine vessels, fuel tanks inside transport
vehicles and large storage tanks used to contain bulk
30   volumes of flammable or volatile materials. For
example, fires and explosions inside aircraft fuel tanks
are usually caused by an electrical source inside a fuel
tank producing a spark that ignites the mixture of fuel
vapour and air which has built up in the headspace of
35   the tank. During refuelling, a static charge in the

filling nozzle of the fuel tank can also ignite vapour
that has been released from the aviation fuel. Although
rare, the consequences of a fire or explosion in an
aircraft fuel tank are invariably catastrophic.

5   Improvements in the safety of aircraft fuel tanks
have tended to concentrate on minimising the ignition
sources that can come into contact with the fuel vapour
in the headspace of the fuel tank. However, aviation
safety authorities have recently recognised that

10   incorporating an inert atmosphere in the headspace of
aircraft fuel tanks would also significantly reduce the
risk of fire and explosion.

         Fuel tanks and other storage tanks on board ships,
warships and oil/gas platforms also provide a potential

15   risk of fire and explosion, and again a nitrogen
inerting system would provide a cost effective means of
reducing this risk.

         With regard to transport vehicles, static charges
generated in the filling neck of a fuel tank during

20   refuelling can ignite the vapour released from the more
volatile conventional petroleum fuels, for example, such
as petrol.

         However, the flame is unable to propagate down the
fill pipe into the fuel tank because the mixture of

25   petrol vapour and air in the pipe is too rich, i.e.
there is not enough oxygen in the mixture to support
combustion. Consequently the risk of fuel tank fires
and explosions with conventional transport fuels is
extremely low.

30   Alternative transport fuels are being developed as
substitutes for conventional fuels, and some of these
are more volatile and flammable than their petroleum
counterparts. There is therefore an increased risk that
whilst filling the fuel tank with these particular

35   fuels, the mixture of fuel vapour and air in the neck of

the tank may accidentally ignite under normal
temperature conditions.

For example, E-Diesel, a blend of 15% natural
ethanol and 85% diesel, has been developed as an
5   alternative fuel for commercial transport vehicles.
Because the natural ethanol constituent is manufactured
from renewable energy resources, E-Diesel has
significant environmental benefits. Ethanol and diesel
are immiscible and blending agents are used to form a
10 mixture of the two materials.

The ethanol and the diesel in the blended fuel
retain their individual vapour pressures, and at normal
ambient temperatures the headspace in the fuel tank is
therefore mainly filled with the more volatile ethanol
15 vapour. Unfortunately, the low flash point and greater
flammability of the ethanol vapour increases the risk
that during refuelling a static charge could ignite the
ethanol vapour present in the neck of the tank. Because
of the stoichiometric concentration of the ethanol
20 vapour under normal temperature conditions, the flame
could then potentially travel down into the fuel tank
and cause a catastrophic failure.

GB 2397821 describes a method of using the
aforementioned hollow fibre membrane to produce nitrogen
25 rich air on board aircraft for use as an inert
atmosphere inside the fuel tanks of the aircraft. The
gas separation module described in this particular
patent application was based on a traditional design of
module, where a very large number of individual
30 membranes are cut to an appropriate size and they are
then densely packed, in a substantially parallel manner,
into the module. The individual membranes are potted
into polymer potting compound in the module, not only to
hold the membranes in place inside the module but also
35 to slightly separate the membranes from each other so

that air can circulate around the outside of the
membranes. This type of gas separation module is
therefore bulky and the large amount of potting compound
required to hold the membranes in place adds to the
5   weight of the module.
         The present invention seeks to provide an improved
gas separation module that uses the unique low pressure
properties of the permeable hollow fibre membrane in a
manner whereby the module can be of a much more compact,
10   as well as lightweight, construction. A compact and
lightweight energy efficient nitrogen inerting system
would be particularly advantageous for transport
applications, such as on board aircraft and inside
vehicles, where weight and space are especially
15   important.
         One way of achieving a more compact membrane
arrangement would be to wind lengths of hollow fibre
membrane in a substantially spiral manner around a
hollow tube located inside the gas separation module,
20   instead of aligning separated straight strands of
membrane in a parallel fashion along the length of a
module. Spirally wound hollow fibre gas separation
devices are well known in the art; however, such devices
invariably have to operate under high pressures to
25   obtain effective separation, and the in-feed air is
usually pressurised to at least 50 psi and could even be
as high as 100 psi.
         From a first broad aspect, therefore, the present
invention provides a low pressure method of gas
30   separation that comprises a plurality of strands of
hollow fibre membrane arranged in a substantially
spiral, entwined manner inside a lightweight gas
separation module.
         In a preferred embodiment the present invention
35   provides an energy efficient gas separation system

wherein a very long length of the permeable composite
hollow fibre membrane is wound around a hollow support
tube in a manner whereby the wound layers are closely
packed together and are in direct contact with one
5   another. The membrane is preferably wound spirally
around a hollow support tube that is preferably
manufactured from a lightweight metal or other
lightweight material. The enmeshed and layered membrane
structure can then be cut at each end to form a bundle
10   of closely entwined stands of membrane that can then be
potted into a compact and lightweight gas separation
module.

The hollow fibre membrane would typically be at
least 1 km in length and more probably the membrane
15   would be at least 1.5 km in length. It is important
that the relatively long length of membrane is wound
around the metal tube in a carefully controlled manner
so as to avoid compression or constriction that could
subsequently disrupt the flow of air through the hollow
20   core of the membrane. When the wound membrane is cut, a
compact bundle of a very large number of closely
intertwined individual membranes is formed. For
example, there could be hundreds or even thousands of
individual strands of membrane depending on the original
25   length of membrane that was wound onto the tube.

A light vacuum applied to the hollow cores of the
intertwined membranes draws air through the wall of the
membranes and the air is selectively enriched with
oxygen. The retentate air remaining on the outside of
30   the membranes becomes increasingly enriched with
nitrogen as the retentate air slowly passes over the
outside of the closely intertwined membranes located
inside the gas separation module.

The oxygen rich air may be drawn from the hollow
35   cores of the membranes by the permeate vacuum pump. The

retentate nitrogen rich air is drawn from the hollow
core of the metal tube situated at the centre of the
intertwined strands of membrane by either a very light
vacuum or other light means of air displacement. The
5   flow rate of the permeate oxygen rich air from the
membrane is preferably much higher than the flow rate of
the retentate nitrogen rich air. By way of example, a
nitrogen inerting gas separation module for use in
transport vehicles may produce typical flow rates of
10   about 30 litres/minute and 2 litres/minute for the
permeate and retentate air streams respectively.

The different flow rates of the permeate and
retentate air streams also have an effect on the
composition of the oxygen and nitrogen rich air
15   fractions. For example, the permeate air from the gas
separation module is generally only slightly enriched
with oxygen and would typically contain about 22%
oxygen, i.e. have a composition of 22% oxygen and 78%
nitrogen. In contrast, the retentate air gradually
20   becomes highly enriched with nitrogen as it passes over
the membranes and would typically contain about 10%
oxygen, i.e. a composition of 10% oxygen and 90%
nitrogen, or even less, by the time the retentate air
leaves the gas separation module. In various
25   embodiments the purity, i.e. composition, and the rate
of production of nitrogen enriched air is varied by
changing the flow rate of the nitrogen and/or oxygen
enriched air out of the gas separation module, and/or by
changing the pressure at which air is allowed to enter
30   the gas separation module. The purity and/or rate of
production of oxygen enriched air can be varied in a
corresponding manner.

Various embodiments of the gas separation module
for the nitrogen inerting system will now be described,

by way of example only, and with reference to the
accompanying drawings in which:

Figure 1A is a schematic cross-sectional
illustration showing the main components used in the
5   construction of the preferred gas separation module,
Figure 1B shows the hollow fibre membrane after it has
been completely wound around the hollow metal tube of
the gas separation module and Figure 1C shows the
membranes after they have been cut, potted and fixed
10   into place inside the gas separation module.

Figures 2A and 2B illustrate internal end views of
two types of end caps that could be used in the
construction of the preferred embodiment.

Figure 3A is a side view showing the potted
15   membranes partly covered by protective film. Figure 3B
is a side view showing the completed gas separation
module fitted with one example of an external protective
cover.

Figure 4 is a schematic illustration of the gas
20   separation module connected to a vacuum pump.

Figure 5 is a schematic illustration of the
preferred embodiment connected to a commercial fuel
tank.

Figure 6 shows a graph of the oxygen content in the
25   headspace of a fuel tank which is connected to the
preferred embodiment against time.

Figure 7 is a schematic illustration of a preferred
embodiment suitable for use in an aircraft flying at
cruising altitude.

30   Figure 8 is a schematic illustration of a preferred
embodiment suitable for use in an aircraft flying at
various altitudes.

Figure 9A illustrates end and side views of the end
caps used in the construction of another preferred
35   embodiment. Figure 9B is a side view of an embodiment

showing the potted membrane partly covered by an
impermeable film. Figure 9C is a side view showing the
completed gas separation module fitted with a preferred
external protective cover.

5   With reference to Figures 1 and 2, the main
components of the gas separation module are a hollow
metal tube 1, preferably made from a rigid and
lightweight material, more preferably from a lightweight
metal such as aluminium or aluminium alloy, and two

10   metal end caps 2 and 3, which may also be made from
lightweight metal or some other rigid lightweight
material. The metal tube 1 has a series of perforations
12 through the wall of the tube that allow air to pass
through the wall of the metal tube into the hollow core

15   of the tube. The perforations 12 may be situated near
the end of tube 1 that will eventually be fixed to end
cap 3 by means of locking nut 11, and this end of tube 1
is left open.

       The opposite end of the metal tube 1 is fixed to a

20   hollow metal fitment 7, which blocks off this end of
tube 1. The fitment 7 has openings 13 that allow air to
pass through the fitment 7. The free end of fitment 7
is left open and fitment 7 will eventually be fixed to
end cap 2 by means of locking nut 6.

25   As shown in Figure 2A, end cap 2 may have a
circular outer wall 4 and a circular inner wall 5 so
that a recess is formed between the outer wall 4 and the
inner wall 5. This recess could incorporate a series of
holes to allow air to enter the gas separation module,

30   similar to those illustrated on end cap 3 in Figure 2B.
The enclosed space between the inner wall 5 of the end
cap 2 and the outside of tube 1 forms a small reservoir
for the polymer potting compound that will eventually
secure the open ends of the cut hollow fibre membranes

35   in place inside the gas separation module.

In the preferred embodiment a circular hole 21 is
provided at the centre of the base of cap 2, which
allows the end of fitment 7 to protrude through cap 2 so
that it can be locked in place by locking nut 6.

5   As shown in Figure 2B, end cap 3 may have a
circular outer wall 8 and a circular inner wall 9 so
that a recess is formed between the outer wall 8 and the
inner wall 9. The recess is preferably perforated with
a series of holes 10, which eventually allow atmospheric

10   air to pass through end cap 3 into the gas separation
module. The enclosed space between the inner wall 9 of
cap 3 and the outside of tube 1 forms a small reservoir
for the polymer potting compound that will eventually
hold the closed ends of the hollow fibre membranes in

15   place inside the gas separation module.
        There is a circular hole 22 at the centre of the
base of cap 3, which allows the end of tube 1 to
protrude through cap 3 so that it can be locked in place
by locking nut 11.

20   A long length of membrane, i.e. a length of 1 km or
more of membrane, is then wound around tube 1 in a
carefully controlled manner. The first layer of
membrane is wound spirally around tube 1 at an inclined
angle, for example, of about 45°, with the membrane

25   inclined from right to left. After the first layer has
been wound onto tube 1, the second layer is wound over
the first layer at an angle of, for example, 45°, but
with the membrane then inclined from left to right. The
direction of the incline is then reversed on each

30   subsequent layer until eventually the whole membrane has
been wound onto tube 1 in a large number of reversed
layers. For example, there could be hundreds or even
thousands of layers of membrane wound around tube 1,
preferably in a criss-cross fashion, depending on the

35   original length of membrane.

This is illustrated schematically in Figure 1B,
which shows the complete membrane wound onto tube 1.
The membranes of layers 14 are inclined at an angle from
right to left, whilst the membranes of the lower layers
5   15 are inclined from left to right. The left hand end
of the wound bundle of membranes is then completely cut
through along a line marked from A on Figure 1B. This
exposes the open ends of the individual strands of
membrane that have been formed from the large number of
10 separate layers of membrane wound around tube 1.

As shown in Figure 1C, the exposed ends of the
membranes are then potted into reservoir 17 in end cap 3
by potting compound 18, so that the ends are completely
sealed and airtight, and tube 1 is fixed to end cap 3 by
15 locking nut 11. The potting compound also helps to seal
tube 1 to end cap 3. The right hand end of the wound
bundle of membranes is then completely cut through along
a line marked from B on Figure 1B. This exposes the
opposite open ends of the strands of individual membrane
20 that have been wound onto tube 1. As shown in Figure
1C, the exposed ends of the membranes are then potted
into reservoir 19 in end cap 2 by potting compound in a
manner whereby the ends of the membranes are open and
lead to an evacuation chamber 20 formed inside cap 2.
25 The end of fitment 7 is fixed to end cap 2 by locking
nut 6, and the potting compound also helps to seal
fitment 7 in place in cap 2. In fact, to facilitate
manufacture, the membranes may be potted into the
potting compound first and the potted end then cut
30 through to expose the fibre ends.

The method of manufacture described in relation to
Figures 1B and 1C results in a structure with a very
large number of densely packed and intertwined membranes
that can effect gas separation, i.e. structure 16 in
35 Figure 1C, which in turn allows the gas separation

module containing the membranes to be of a very compact construction.

With reference to Figure 3A, the entwined membranes 16 (shown in Figure 1C) may be wrapped in a thin plastic
5   film 23, except for a small portion of the membranes 24 adjacent to end cap 2 which would be left exposed to the air entering the module. The plastic film may be preferably of a polymer type that may be permeable to air at high pressures but impermeable to air at the low
10 pressures (e.g. ≤ 30 psi) prevailing inside the gas separation module. Alternatively, the plastic film could cover the whole length of the entwined membranes 16, and the film would be suitably perforated so as to allow air to pass through the film at a flow rate that would be
15 appropriate to the relative position in the bundle of membranes. For example, there would be very few perforations in the film near end cap 3 so that the flow of air into the bundle of membranes close to end cap 3 was restricted. The number of perforations would then
20 gradually increase across the width of the film, which could allow the flow of air through the film and into the bundle of membranes to correspondingly increase   . until the highest flow rate was achieved adjacent to end cap 2.
25   As seen in Figure 3B, rigid cylindrical protective outer cover 25, manufactured from either lightweight metal or a lightweight material, such as a composite or a plastic material, may then be fitted around the outside of end caps 2 and 3. An exit tube 26 is fitted
30 to locking nut 6 to allow removal of the permeate oxygen rich air from the gas separation module, and an exit tube 27 is fitted to locking nut 11 to allow removal of the retentate nitrogen rich air from the gas separation module.

In an alternative-embodiment shown in Figures 9A-9C
the diameter of end caps 2 and 3 could be reduced by
eliminating the outer recesses of the end caps that
provide inlet ports to allow air to enter the gas
5   separation module. Wall 5 on cap 2 and wall 9 on cap 3
(see Figures 2A and 2B) would then become the external
walls of the end caps, and this would result in a much
narrower gas separation module. An inlet port or ports
to allow air to enter the module could be provided in
10   the protective cover 25 that is fitted to the outside of
the module.

Instead of using a single very long length of
hollow fibre membrane in the construction of the gas
separation module, it is feasible that a number of
15   shorter, albeit still relatively long lengths of
membrane, could be used to produce the membrane strands
that are used to effect gas separation inside the
module. The membrane strands are preferably entwined.
For example, instead of using a single hollow fibre
20   membrane 1 km long, it would be feasible to use say four
shorter membranes each of 0.25 km in length, or five
membranes each of 0.2 km in length, or ten membranes
each of 0.1 km in length, or even a combination of
different lengths of membrane. The multiple lengths of
25   membrane could be wound simultaneously or consecutively
onto the hollow tube 1, preferably in a carefully
controlled criss-cross manner, until the requisite
length of membrane has been wound onto the tube.

The individual intertwined gas separation membranes
30   would then be formed from the wound bundle by cutting
each end of the bundle and the membranes would be potted
as described earlier. The gas separation module would
then operate in much the same way as a module formed
from a single long length of hollow fibre membrane.

The operation of the gas separation module will now
be described with further reference to Figures 1A, 1B,
2A, 3A and 3B.

A light vacuum of about 0.5 bar applied to tube 26
5   draws air from the evacuation chamber 20. The vacuum
then builds up in the hollow cores of the densely
packed, intertwined membranes until eventually the
atmospheric air on the outside of the membranes is drawn
through the walls of the membranes and the air is
10   selectively enriched with oxygen. The permeate oxygen
rich air is released to the outside atmosphere by tube
26.

Atmospheric air may, in one embodiment, enter the
gas separation module through the perforated holes 10 in
15   end cap 3. As the vacuum builds up inside the hollow
cores of the membranes, the atmospheric air is drawn
into the exposed portion of the wound membranes 24,
which may be close to end cap 2. The air then
percolates under the protective film 23 and the air
20   gradually passes over the outside of substantially all
of the intertwined membranes.

As the air slowly washes over the outside of the
membranes, it becomes increasingly enriched with
nitrogen as permeate oxygen rich air is drawn through
25   the walls of the membranes by the vacuum in the hollow
cores of the membranes. Eventually the retentate
nitrogen rich air passes through the perforations 12 in
metal tube 1 into the hollow core of the tube.

A very light vacuum of say less than 0.1 bar, or
30   some other light means of air displacement, applied to
the exit tube 27 draws the retentate nitrogen rich air
out of the hollow core of tube 1. This light vacuum
also encourages more atmospheric air to enter the gas
separation module through the perforations 10 in end cap

3 and wash across the outside of the intertwined
membranes.

The retentate air leaving the module through the
exit tube 27 is rich enough in nitrogen to be used
5   directly as an inert atmosphere inside fuel tanks.
Typically the permeate oxygen rich air leaving the
module in tube 26 would consist of 22% oxygen, 78%
nitrogen, and the retentate nitrogen rich air leaving
the module in tube 27 would consist of about 10% oxygen,
10 90% nitrogen.

As the hollow fibre membrane used in the gas
separation module is able to separate air into oxygen
and nitrogen rich fractions by means of a low pressure
differential across the wall of the membrane, under
15 certain practical conditions it might well be feasible
to augment the negative vacuum pressure on the inside of
the membrane with a slight positive pressure on the
outside of the membrane. For example, certain road
vehicles, such as lorries and buses, have a supply of
20 compressed air available to assist braking, whilst
passenger aircraft use compressed air from the aircraft
engines to supply fresh pressurised air to the air
conditioning system inside the aircraft. Under these
circumstances, the pressurised air may be introduced to
25 the outside of the membranes preferably at a slight
positive pressure of say 5 to 10 psi relative to the
ambient atmospheric pressure (i.e. cabin pressure in an
aircraft). A negative vacuum pressure of say 5 to 8 psi
relative to the ambient atmospheric pressure could be
30 simultaneously applied to the inside of the membranes.
The positive and negative pressures could therefore be
arranged so as to produce a differential working
pressure across the walls of the membranes that would
provide effective air separation.

Providing the pressure of the in-feed air is only
slightly above the ambient atmospheric pressure, for
example a positive pressure of less than 10 psi relative
to the ambient atmospheric pressure, the gas separation
5   module would not need to be highly pressure resistant,
although it would have to be air tight, and the module
could therefore still be manufactured from lightweight
materials. Obviously, there would be significant energy
savings if a supply of compressed or pressurised air was
10   readily available for the gas separation process. In
addition, the inherent positive pressure on the outside
of the membranes would naturally displace the retentate
air from the module and a retentate vacuum pump would
not be required.
15   The volume and the composition of the retentate
nitrogen rich air can be varied in a number of ways
including, for example, by altering the gas separation
properties of the hollow fibre membrane; by changing the
length of hollow fibre membrane packed into the module;
20   and by altering the relative pressures and flow rates of
the permeate and retentate air streams.
          For example, the vacuum on the permeate oxygen rich
air stream could be varied between say 0.4 bar and 0.8
bar, although preferably the permeate vacuum would
25   typically be between 0.4 and 0.6 bar, whilst the vacuum
on the retentate nitrogen rich air stream would
preferably be no more than 0.1 bar. Alternatively, a
lighter vacuum could be used inside the membrane if the
air being introduced into the module was lightly
30   pressurised, and in this case the positive pressure on
the outside of the membrane could also be varied to
change the volume and/or composition of the nitrogen
rich retentate air being produced by the gas separation
module. The following Table 1 also illustrates how
35   altering the flow rate of the retentate air stream can

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significantly affect the nitrogen content of the
retentate air. The measurements given in Table 1 were
obtained from a typical nitrogen inerting module
operating in a manner whereby the permeate air stream
5   was maintained at a constant vacuum relative to the
atmospheric pressure of the intake air, whilst the flow
rate of retentate air was varied by altering the vacuum
applied to the retentate air stream.

TABLE 1

10   Nitrogen Content of the Retentate Air
             Under Different Retentate Flow Rates

Retentate Flow Rate Litres/minute	Composition of the Retentate Air	Permeate Vacuum Psi
8.0	15% oxygen, 85% nitrogen	-11.2
6.0	13% oxygen, 87% nitrogen	-11.2
4.0	11% oxygen, 88% nitrogen	-11.2
2.0	9% oxygen, 91% nitrogen	-11.2
1.0	6% oxygen, 94% nitrogen	-11.2
0.5	5% oxygen, 95% nitrogen	-11.2

      Being able to readily vary the flow rate and/or the
15 composition of the retentate nitrogen rich air is a
particularly important requirement for certain end-use
applications. For example, to adequately inert the fuel
tanks onboard an aircraft throughout the flight of the
aircraft, the nitrogen inerting system needs to be able
20 to produce low flow rate, high purity nitrogen rich air
whilst the aircraft is in climb and cruise modes, and

high flow rate, low purity nitrogen rich air during the
descent of the aircraft.

        The volume of nitrogen rich air available for
inerting purposes can also, of course, be increased by
5   operating a multiplicity of gas separation modules
together in parallel.

        Alternative nitrogen inerting systems, based on the
principles described above, have been developed for
different end-use applications, and some typical
10 examples are described below.

                            Example 1
        The first example is a relatively simple
application involving the supply of an inert atmosphere
15 to the fuel tank of a prototype racing sports car
fuelled by natural ethanol. The flammability and
volatility of the ethanol fuel poses a fire risk during
refuelling under race conditions, and a nitrogen
inerting system was therefore developed for the racing
20 car. The inerting system is described with reference to
Figure 4.

        A 1.5 km length of the composite hollow fibre
membrane, produced by the method disclosed in GB
2397303, and in the form of a multitude of intertwined
25 strands of membrane, is contained inside the gas
separation module 25. Exit tube 26 is connected to a
vacuum pump 28 so that the hollow cores of the
intertwined membranes can be subjected to a vacuum of
about 0.5 bar. The vacuum pump draws permeate oxygen
30 rich air 29 from the gas separation module at a rate of
about 30 litres/minute.

        In this particular application, under racing
conditions the sports car has high fuel consumption and
the ethanol fuel is used at an average rate of about 3
35 litres/minute. The fuel level therefore falls quickly

inside the fuel tank and the resulting pressure drop in
the tank is sufficient to draw the retentate nitrogen
rich air 30 directly from the gas separation module 25
into the fuel tank, without the assistance of an
5   additional air displacement pump. Under these
particular operating conditions, the nitrogen rich air
30 from the gas separation module 25 would contain about
11% oxygen, i.e. the inert air would have a typical
composition of 11% oxygen, 89% nitrogen. The exit tube
10   27 containing the nitrogen rich air 30 may be connected
directly into the mouth of the fuel tank inside the
racing car.
     As the fuel level drops, inert nitrogen rich air 30
is automatically sucked from the gas separation module
15   25 into the fuel tank, whilst the permeate oxygen rich
air 29 from the vacuum pump 28 is released into the
outside atmosphere.
     The inert nitrogen rich air 30 accumulates in the
mouth and the filling neck of the fuel tank, and builds
20   up in the headspace of the fuel tank. The inert
nitrogen rich atmosphere in the mouth of the tank helps
to reduce the risk of a static charge accidentally
igniting ethanol vapour during refuelling.
     Even if the ethanol vapour in the mouth of the tank
25   did ignite, the inert atmosphere in the filling neck of
the fuel tank would prevent the flame propagating down
into the fuel tank. An inert atmosphere in the fuel
tank is also an additional safety feature in the event
of the sports car suffering either an accident or impact
30   damage during racing.
     The properties of the nitrogen inerting system
developed for the motor racing sports car are summarised
in Table 2.

                          Table 2
35   Nitrogen Inerting System

For a Racing Sports Car Fuelled by Natural Ethanol

Property	Value
Length of hollow fibre membrane	1.5 km
Diameter of the gas separation module	10 cm
Length of the gas separation module	38 cm
Volume of the gas separation module	3 litres
Weight of the gas separation module	< 1.5 kg
Sports car fuel consumption	180 litres/hour
Flow of nitrogen rich air into fuel tank	3 litres/minute
Typical composition of nitrogen rich air	11% oxygen, 89% nitrogen
Vacuum on permeate air stream	Approx. 0.5 bar
Flow of oxygen rich air to atmosphere	30 litres/minute

Example 2

5   Figure 5 illustrates a nitrogen inerting system
developed for commercial transport vehicles that would
be fuelled by a volatile fuel such as the E-Diesel blend
of ethanol and diesel.

        There are significant performance differences
10   between commercial transport vehicles and the motor
racing sports car described in Example 1. For example,
a typical commercial transport vehicle probably has an
average fuel consumption of between 10 and 20
litres/hour, whereas the motor racing car has a fuel
15   consumption of about 180 litres/hour.

        With reference to Figure 5, a vacuum pump 28 draws
the oxygen rich air 29 from the gas separation module 25

through exit pipe 26 and the oxygen rich air 29 is
released into the atmosphere. The fuel consumption of a
normal commercial transport vehicle would be
insufficient to create a differential pressure in the
5 fuel tank 32 that would be reliable enough to draw the
inert nitrogen rich air 30 from the gas separation
module 25 into the tank. A light vacuum pump 31 is
therefore used to displace the nitrogen rich air 30 from
the gas separation module 25 into the fuel tank 32.

10   Figure 5 illustrates a typical commercial fuel tank
32, which has a filling neck 34 leading to a filling
pipe 33 connected to the fuel tank 32. The filling neck
34 is sealed by a filling cap 36. The light pump 31
feeds the nitrogen rich air 30 into the mouth 35 of the
15 filling neck 34 and the inert air 30 then gradually
percolates down the filling pipe 33 into the headspace
of the fuel tank 32.

As the inert nitrogen rich air 30 accumulates in
the mouth 35, the filling neck 34, the filling pipe 33
20 and the headspace of the fuel tank 32, the atmosphere
becomes increasingly more inert. It is therefore
extremely unlikely that a static charge generated in the
mouth 35 of the filling neck 34 during refuelling would
be able to ignite any ethanol vapour present in the
25 mouth of the fuel tank. Even if the ethanol vapour did
ignite, the inert atmosphere in the filling neck 34 and
the filling pipe 33 would inhibit combustion and the
flame would not be able to spread down into the fuel
tank 32.

30   The fuel tank may be fitted with a venting pipe 37
that allows any excessive build-up of fuel vapour 39 in
the headspace of the tank 32 during relatively warm
conditions to be vented either to the outside atmosphere
or to the air intake of the engine. The venting process
35 is controlled by a pressure relief valve 38. The

pressure of the nitrogen rich air 30 supplied into the
fuel tank 32 by pump 31 would not, on its own, be high
enough to activate the pressure relief valve 38.

5   Venting systems vary between different fuel tanks.
For example, some tanks vent fuel vapour back into the
mouth of the fuel tank, and a pressure relief filling
cap is used to allow excessive build-up of vapour to be
released into the atmosphere. The nitrogen inerting
system described in Figure 5 should be able to work
10   satisfactorily with any of the normal methods employed
to vent fuel tanks.

The nitrogen inerting system was tested under
simulated conditions by using a 200 litre fuel tank 32
filled with E-Diesel fuel. Initially, the headspace
15   over the fuel in the tank 32 was filled with normal
atmospheric air, i.e. air with a composition of 21%
oxygen, 79% nitrogen. The flow of fuel from the tank 32
was set at a constant flow rate of 20 litres/hour, and
the flow of nitrogen rich air 30 from the gas separation
20   module 25 into the tank 32 was controlled at 1.5
litres/minute. The oxygen content of the air in the
headspace of the fuel tank 32 was measured at regular
intervals.

As shown by the graph in Figure 6, under the above
25   test conditions an inert atmosphere, i.e. air containing
less than 13% oxygen, was achieved in the headspace of
the fuel tank 32 in less than 40 minutes and after 60
minutes the inert air in the headspace of the tank 32
contained only 11.5% oxygen. The air in the headspace
30   then gradually became increasingly more inert until
after 5 hours running, by which time the tank was only
half full of fuel, the air was extremely inert and
contained only 7% oxygen, i.e. an air composition of 7%
oxygen, 93% nitrogen.

At an oxygen concentration of 7%, the very inert
atmosphere inside the fuel tank 32 would also help to
reduce the risk of fire in the event of either an
accident or an impact that damaged or ruptured the fuel
5   tank 32.

Because nitrogen rich air 30 is continually fed
into the fuel tank 32 by the nitrogen inerting system
whenever the engine of the vehicle is running, an inert
atmosphere is always maintained in the filling neck and
10   in the headspace of the fuel tank. When the vehicle is
parked and the engine is not running, most fuel tanks
are airtight enough to be able to retain the inert
atmosphere inside the tank for an appreciable length of
time.

15   The properties of the commercial transport vehicle
nitrogen inerting system, as tested in the laboratory,
are summarised in Table 3.

Table 3

20   Nitrogen Inerting System
For a Commercial Transport Vehicle Fuelled by E-Diesel

Property	Value
Length of hollow fibre membrane	1.5 km
Diameter of the gas separation module	10 cm
Length of the gas separation module	38 cm
Volume of the gas separation module	3 litres
Weight of the gas separation module	< 1.5 kg
Tested fuel consumption	20 litres/hour
Vacuum on retentate air stream	Less than 0.1 bar

Flow of nitrogen rich air	1.5 litres/minute
Composition of nitrogen rich air	Down to 7% oxygen, 93% nitrogen
Vacuum on permeate air stream	Approx. 0.8 bar
Flow of oxygen rich air	30 litres/minute

A supply of compressed air may also be available from the braking systems used in many commercial transport vehicles, and if the normal atmospheric air being fed into the air separation module was replaced by slightly pressurised air then the vacuum applied to the inside of the membranes could be reduced accordingly. The positive pressure on the outside of the membranes would also displace the retentate air from the module and a retentate vacuum pump would not be required.

Example 3

Large passenger aircraft fly at high altitudes, typically a height of about 11000 metres, in order to conserve fuel and achieve an adequate flight range. Although the atmospheric air composition remains the same irrespective of altitude, i.e. 21% oxygen, 79% nitrogen, the atmospheric pressure decreases as altitude increases, as illustrated in Table 4.

A reduction in atmospheric pressure is accompanied by a decrease in the ability of humans to transfer oxygen from the lungs to the bloodstream, an effect known as hypoxia. To protect passengers and crew from hypoxia, passenger aircraft flying above 3000 metres are therefore pressurised to compensate for the reduced atmospheric pressure.

Table 4

Ambient Pressure at Different Altitudes

Altitude (Feet)	Altitude (Metres)	Ambient Pressure (KPa)	Ambient Pressure (PSI)
0	0	101.4	14.7
4750	1448	84.0	12.19
8000	2438	76.7	10.83
10000	3048	72.0	10.44
12000	3658	64.0	9.28
15000	4572	57.4	8.35
17500	5334	50.7	7.35
25000	7620	38.6	5.6
36000	10973	22.7	3.29
40000	12192	18.7	2.71
44000	13411	16.0	2.32
60000	18288	7.3	1.06

To allow an aircraft to be pressurised, the

5   fuselage has to be strengthened so that the fuselage can
act as a pressure vessel. However, strengthening the
fuselage has a detrimental impact on the fuel
consumption and hence the potential range of the
aircraft. The cabin pressure is therefore usually

10   maintained at about 10.83 psi (74.7 kPa), which is
equivalent to the atmospheric pressure at an altitude of
about 2400 metres, to reduce the amount of strengthening
required to the airframe.

Figures 7 and 8 illustrate two alternative nitrogen

15   inerting systems that could be used on board passenger
aircraft to provide an inert atmosphere in the fuel
tanks of the aircrafts.

Figure 7 illustrates a relatively simple nitrogen
inerting system, which utilises the differential

20   pressure that is naturally available when a passenger
aircraft is flying at its cruising altitude, i.e. the

pressure differential between the cabin pressure inside
the aircraft and the atmospheric pressure outside the
aircraft.

The gas separation module 40, which would include a
5   very large number of individual intertwined hollow fibre
membranes, would be located in the air conditioning
system that supplies pressurised air to the passenger
cabins of the aircraft. Up to 22 m³/hour of inert
nitrogen rich air 46 would need to be delivered to the
10   fuel tanks of the aircraft to replace the fuel being
burned by the aircraft when it is flying at its normal
cruising altitude.

Although a single gas separation module 40 is
illustrated in Figure 7, in practice a multiplicity of
15   modules, operating together in parallel, may be needed
to produce this amount of inert air 46.

The air transport regulatory authorities specify
that each passenger on an aircraft should be supplied
with about 10 ft³/min (0.28 m³/min) of fresh air. On
20   large passenger aircraft, which can carry up to 550
passengers plus crew, this amount of fresh air per
passenger is equivalent to a total air supply of about
165 m³/minute or 9900 m³/hour. The amount of
pressurised cabin air required to produce 22 m³/hour of
25   inert nitrogen rich air is therefore virtually
insignificant compared to the total amount of fresh air
supplied to the passenger cabins of an aircraft.

In the simple nitrogen inerting system illustrated
in Figure 7, the gas separation module 40 is operated by
30   means of the differential pressure that exists between
the inside and the outside of an aircraft flying at its
cruising altitude, and no additional pumps are required
in the system. For example, in an aircraft cruising at
a height of 11000 metres the cabin pressure is 10.83 psi
35   (74.7 kPa) whilst the atmospheric pressure outside the

aircraft is 3.29 psi (26.9 kPa), and the resulting
pressure differential of 7.54 psi (52.0 kPa) would be
sufficient to operate the gas separation module 40.

5   In Figure 7, an exit pipe 42, which takes the
permeate oxygen rich air 43 from the module 40, would be
connected to an outlet valve positioned in the airframe
at the rear of the aircraft that would lead directly to
the outside atmosphere. Passenger aircraft are already
fitted with a valved outflow air system that continually
10   discharges stale air from the passenger cabins into the
outside atmosphere. The outlet valve for the reject
permeate air from the gas separation module 40 could
therefore be an integral part of the existing outflow
air system of the aircraft.

15   Opening the outlet valve would create a pressure
differential between the pressurised cabin air 41 being
fed into the module 40, which would be at a pressure of
10.83 psi (74.7 kPa), and the atmospheric air on the
outside of the aircraft, which would be at 3.29 psi
20   (26.9 kPa). This drop in pressure would be sufficient
to pull the cabin air 41 through the walls of the hollow
fibre membranes and selectively enrich the air with
oxygen. The low pressure outside the aircraft would
then draw the reject permeate oxygen rich air 43 from
25   module 40 into the outside atmosphere. Because the fuel
tanks in an aircraft are not pressurised, the exit pipe
45 that takes the nitrogen rich air 46 from the module
40 would be connected to a valve 44, which would bleed
the inert nitrogen rich air 46 into the fuel tanks at
30   the required pressure and flow rate.

The simple nitrogen inerting system illustrated in
Figure 7 is particularly suitable for the 'steady-state'
conditions that exist whilst an aircraft is flying at
its cruising altitude, i.e. where the atmospheric
35   pressures inside and outside the aircraft are reasonably

constant. However, during a flight, different and. variable pressure conditions exist when an aircraft is ascending during takeoff and descending on landing. When the aircraft is on the ground the pressure inside

5   and outside the aircraft is of course at normal ambient ground level conditions.

On landing, the fuel tanks of the aircraft would still contain the nitrogen rich atmosphere that had been supplied by the nitrogen inerting system during the

10 flight. However, the refuelling process on the ground is always a risky operation because a static charge could ignite aviation fuel vapour present in the filling nozzles of the fuel tanks and cause a fire. A continual supply of nitrogen rich air from the nitrogen inerting

15 system to the filling nozzle and the headspace in the fuel tanks whilst the aircraft was being refuelled on the ground would therefore be an additional safety feature.

Figure 8 illustrates modifications to the aircraft

20 nitrogen inerting system that would allow the system to be used under different operating conditions. For example, the air 41 entering the gas separation module 40 would be at normal ambient atmospheric pressure, i.e. 14.7 psi (101.4 kPa), when the aircraft is on the ground

25 and at about 10.83 psi (74.7 kPa) when the aircraft reaches its cruising altitude. To cater for differing pressure conditions the exit tube 42 that takes the permeate air 43 from the gas separation module 40 is connected to a valve 47, and at cruising altitude valve

30 47 allows the permeate air 43 to be passed directly to the outlet valve of the aircraft.

During ascent, descent and whilst the aircraft is on the ground, when the cabin pressure is either at or near ambient atmospheric conditions, valve 47 would

35 divert the permeate air stream to a light vacuum pump

48.   The vacuum pump would then create a pressure drop
in the hollow cores of the membranes in order to
facilitate the gas separation process and the reject
permeate air 49 from the vacuum pump 48 would be
5   released through the outlet valve to the outside
atmosphere.

     Exit tube 45 that takes the retentate nitrogen rich
air from the module 40 is still connected to valve 44.
At cruising altitude, valve 44 would bleed the inert
10   nitrogen rich air 46 into the fuel tanks at the required
pressure and flow rate. However, during ascent, descent
and whilst the aircraft is on the ground, when the cabin
pressure is either at or near ambient atmospheric
conditions, valve 44 diverts the retentate air to a very
15   light pump 50, which positively displaces the inert
nitrogen rich air 51 to the fuel tanks of the aircraft.

     The vacuum pumps 48 and 50 are also able to control
the relative flows of the permeate air and the retentate
air streams respectively. As such, the system is able
20   to deliver the appropriate amount of inert nitrogen rich
air at the required composition to suit particular
operating conditions, i.e. depending on whether the
aircraft was being refuelled on the ground, or if the
aircraft was in takeoff, landing or cruising mode.

25   Compressed bleed air from an aircraft engine, which
may be at a pressure of 20 to 30 psi, is used to
pressurise the passenger cabins of the aircraft. A
supply of compressed air is therefore available within
the aircraft air conditioning system and pressurised air
30   could be supplied to augment the pressure differential
across the membranes in the air separation module. For
example, instead or introducing air into the membrane
module at the ambient cabin pressure of 10.83 psi during
cruise mode, the air supplied to the air separation
35   module could be further pressurised to say about 16 psi,

i.e. a positive pressure of 5 psi relative to the ambient cabin pressure. The pressure at which air is allowed to enter the gas separation module may be controlled by a bleed valve. Being able to utilise a

5   positive pressure on the outside of the membranes, in addition to the negative vacuum pressure available on the inside of the membranes, would be particularly useful when the flow of nitrogen rich air has to be rapidly increased to ensure an adequate supply of inert

10   gas to the fuel tanks, such as when the aircraft moves from cruise mode to descent mode.

The examples described show how the nitrogen inerting system would be able to provide an inert atmosphere in the headspace of tanks or vessels

15   containing volatile or flammable materials, such as fuels, solvents and chemicals. Because the nitrogen inerting system is a low pressure system it is safe to use and there is very little risk of a pressure blow out that could damage individual gas separation membranes,

20   or cause damage to either the gas separation module or its immediate surroundings.

A further advantage of the inerting system is that the permeate oxygen rich air from the gas separation module is only very slightly enriched with oxygen, i.

25   e. 22% oxygen instead of the 21% oxygen in normal air. Unlike pure oxygen or air highly enriched with oxygen, both of which can encourage spontaneous combustion, if any permeate oxygen rich air did escape from the gas separating module it would neither encourage combustion

30   nor pose a safety risk.

As shown in the examples, the nitrogen inerting system would be particularly beneficial for fuel tanks used in transport applications, such as in vehicles, ships and aircraft. An inert atmosphere in the filling

35   neck and the headspace of a fuel tank significantly

reduces the risk of a static charge accidentally
igniting fuel vapours in the mouth of the tank during
refuelling. Even if the fuel vapour did ignite the
inert nitrogen rich atmosphere in the filling neck of
5   the tank would not support combustion and the flame
would not be able to spread down into the fuel tank.

An inert atmosphere in the headspace of a fuel tank
also reduces the risk of immediate fire or explosion in
the event of a fuel tank being accidentally punctured or
10   ruptured. By way of example, an inert atmosphere in the
fuel tanks of military vehicles, ships and aircraft
would help to reduce the risk of immediate fire or
explosion if the fuel tank was, for example, punctured
or damaged by shrapnel during battle conditions.
15   Bulk storage tanks for fuels, solvents and
chemicals could also benefit from a nitrogen inerting
system, particularly storage facilities that may be
vulnerable to either man made disasters, such as
potential war zones, natural disasters, such as
20   earthquakes, or terrorist attack.

Examples of more specialised applications for a
nitrogen inerting system could well include the storage
of chemicals and materials that spontaneously ignite,
react, oxidise, degrade or change in nature if they are
25   stored in normal atmospheric air, as well as storage
applications where a low oxygen, anti-corrosive
atmosphere would be beneficial.

Although the present invention has been described
with reference to the preferred embodiments, it will be
30   understood by those skilled in the art that various
changes in form and detail may be made without departing
from the scope of the invention as set forth in the
accompanying claims.

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